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Analysis and Test Support  
for Phillips Laboratory  
Precision Structures

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**AIR FORCE RESEARCH LABORATORY**

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**Report No. 98-11-02**

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This report describes work performed for the Aerospace Structures Information and Analysis Center (ASIAC) under ASIAC Task 35. The work was performed at the Air Force Research Laboratory (AFRL), Phillips Research Site, at Kirtland Air Force Base, New Mexico. ASIAC is funded under Contract F33615-94-C-3200, sponsored by the AFRL, Air Vehicles Directorate, at Wright-Patterson Air Force Base, Ohio. The technical monitor was Captain Rich Cobb of the AFRL, Phillips Research Site.

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## 1. Introduction

This report documents work performed for the Aerospace Structures Information and Analysis Center (ASIAC) under ASIAC Task 35, "Analysis and Test support for Phillips Laboratory Precision Structures." Mr. James Goodding of CSA Engineering was the principal investigator for this task. Mr. Goodding is an integral team member on a number of experiments at the Air Force Research Laboratory (AFRL), Phillips Research Site. Task objectives centered around analysis and structural dynamic test support on experiments within the Space Vehicles Directorate at Kirtland Air Force Base. These efforts help to augment the Air Force's understanding of advanced technology devices and interactions with aerospace structures.

One of the programs supported in this task was the Vibration Isolation and Suppression System (VISS), an AFRL experiment that will fly as part of the Space Technology Research Vehicle-2 (STRV-2) mission. VISS will demonstrate state-of-the-art vibration mitigation technologies for a satellite-based observation platform. Activities included environmental flight qualification test support and participation in the performance test program. The performance testing characterized both open and closed-loop dynamics used to implement the control laws.

The Satellite Ultraquiet Isolation Technology Experiment (SUITE) is another AFRL experiment with many of the same objectives as VISS. Efforts in Task 35 included hardware and software development of the sophisticated active system experiment. Additional efforts included flight hardware acceptance test support for vibration and thermal/vacuum environments prior to delivery to Surrey Satellite Technology Limited (SSTL) for spacecraft integration.

Assistance to the UltraLITE program was included in this effort. UltraLITE will demonstrate the capability to control deployable space structures to nanometer accuracy in the laboratory.

Task 35 funding was also used to support jitter diagnostic and suppression activities at the Starfire Optical Range (SOR). Test support and damping hardware integration into the SOR 1.5-meter telescope was included in this effort.

## 2. Vibration Isolation and Suppression System

The VISS experiment is a six-strut Stewart platform that will demonstrate a number of advanced vibration mitigation technologies on a spaced-based observation platform. These technologies will enable future satellites and instruments with remote sensing and target acquisition/tracking missions to achieve high performance at a lower cost. Vibration suppression techniques incorporated in the VISS system will allow a precision pointing and tracking platform to operate on a "noisy" (and inexpensive) satellite bus. Figure 2 shows the VISS hexapod assembly with a mass mock-up of a medium wavelength infrared (MWIR) payload. The white structure

mounted on the MWIR is a radiator for the payload-mounted cryocooler.

The VISS struts are of a so-called hybrid design that incorporates viscously damped passive elements with an active voice coil actuator. The passive stage is tuned to provide a very low stiffness suitable for low frequency isolation and high performance when on orbit. These passive struts operate by porting fluid between two very soft bellows chambers. Blade flexures at the strut connection to the payload protects the struts from damage due to bending moments.

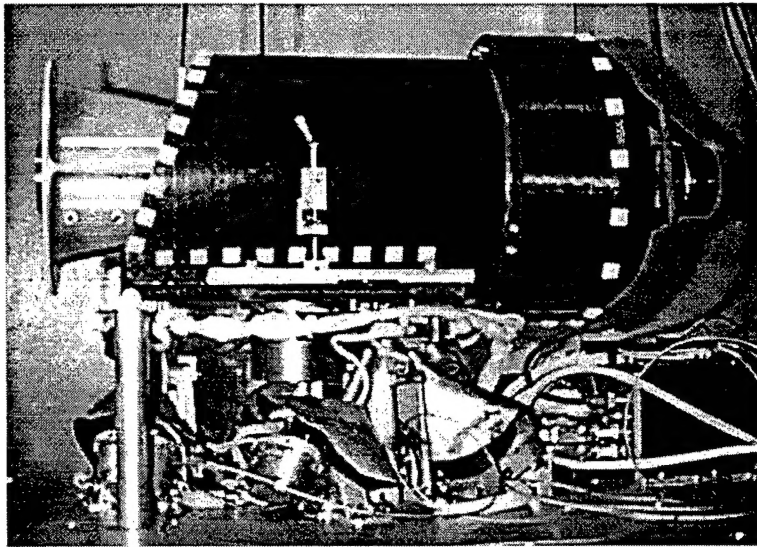


Figure 1: VISS and the MWIR surrogate hardware

The VISS struts are grouped in pairs, with a launch lock at each strut pair. These launch lock systems, consisting of a shape memory alloy bolt (frangibolt) and heater combination, protect the compliant struts from damage under high launch load conditions. These notched bolts fracture when the bolt is heated to a well defined temperature. The MWIR payload will be used on orbit to verify the system performance under open and closed-loop conditions.

Twelve servo-type accelerometers incorporated into the VISS system are used for feedback control and to quantify system performance. Six accelerometers are mounted on the payload, and the remaining are mounted on the strut bases, each sensor aligned with its corresponding strut line of action. The accelerometers are capable of measuring true DC response: a requirement for a system designed to suppress vibration at very low frequencies. In the laboratory the electrical bias generated by the accelerometer being in a one-g field had to be removed to accurately measure the base and payload responses. Four accelerometer break-out boards performed accelerometer signal high-pass filtering and provided analog test points for measurement systems during the ground-based experiments.

The following are the objectives of the VISS space experiment:

- Demonstrate vibration isolation of the payload from motion of the spacecraft. This isolation should be 20 dB or more from 5 to 100 Hz.
- Suppress motion due to the MWIR-mounted cryocooler at its fundamental and lowest two harmonic frequencies.
- Show the capability to actively steer the MWIR with a predetermined profile.
- Demonstrate the effectiveness of combinations of vibration isolation, suppression and steering.

High VISS strut compliance greatly complicated the ground-based “performance” testing. Because the strut compliance is designed to provide good low frequency isolation under mission conditions, the hexapod assembly has insufficient stiffness to support the MWIR payload in a one-g field. The payload must be suspended through other means in a manner to simulate the free boundary conditions of space while having limited influence on the dynamics and system performance. Two sophisticated suspension systems, developed by CSA Engineering, were used to off-load the MWIR while not interacting with the hexapod vibration isolation characteristics.

Performance test objectives included development of control laws and associated real-time command software, and demonstration of the overall VISS test objectives. In addition, the performance tests generated a series of measurements both prior to and following the flight qualification tests. This data base was used to verify that the vibration qualification tests did not degrade the system-level performance in both the passive and active conditions.

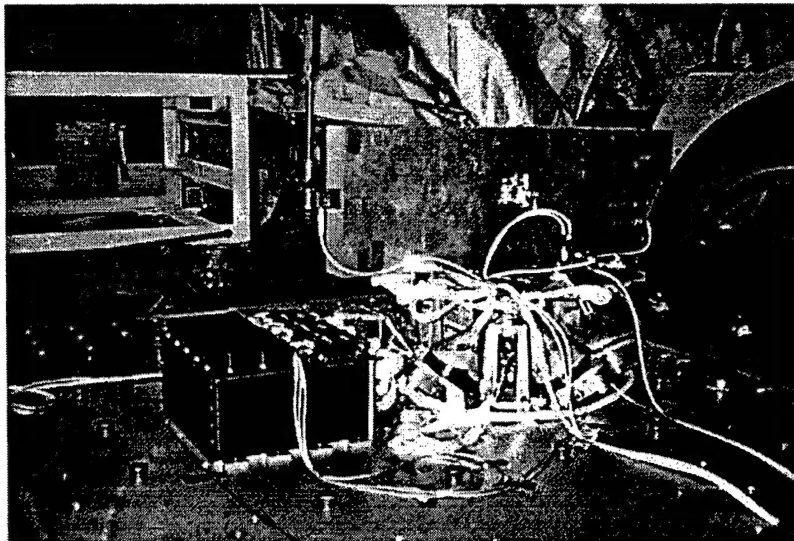


Figure 2: VISS mounted on the shaker slip table

Several small subcontracts were implemented as part of this effort in VISS program support. Trisys, Inc. the primary electronics and software support contractor, resolved problems with downloading and uploading data from the STRV-II spacecraft. In addition, during testing at the Jet Propulsion Laboratory, the instrument was damaged because it was improperly connected to electrical power. The resulting failure was diagnosed and repaired under one of the subcontracts funded by this task.

Use of this contract to support the Air Force Research Laboratory greatly assisted in the progress of this challenging project. The advantage of having on-site test support proved to be instrumental in the daily operations at Kirtland Air Force base. Such assistance greatly increased the Space Vehicles Directorate's experience with space flight hardware.

## 2.1 Flight Qualification Tests

An environmental test series was performed to qualify the hardware for flight. This test series included experiments to simulate launch vibration conditions and the stressing thermal environment like that when on-station. Functional health checks were conducted in both the so-called random vibration and thermal/vacuum tests to verify hardware and electronics operation throughout the test series.

Several failures occurred during the random vibration test program and were corrected. Resulting modifications were verified through test to insure the robustness of the flight hardware under launch and on orbit conditions. While several failures did occur, these types of environmental tests are often used to identify modes of failure and correct any hardware limitations prior to integrated spacecraft flight qualification tests.

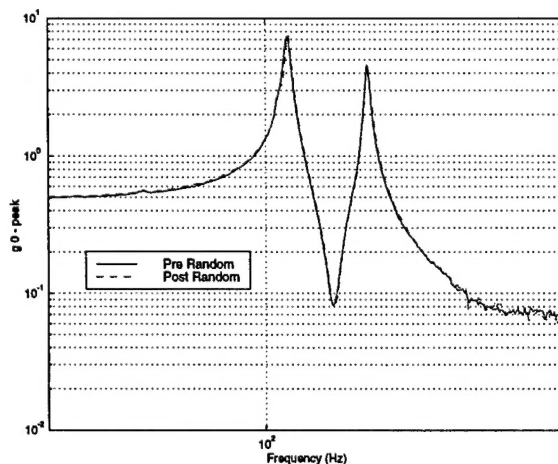


Figure 3: VISS thrust-direction swept sine acceleration spectra

Figure 2 shows the hardware mounted on the shaker slip table. The black box

houses the flight electronics, sensor signal conditioning and on-board computational devices. An aluminum MWIR mass simulator was mounted to the top of the VISS struts and launch lock tower assemblies. This mass model was used to prevent potential damage to the surrogate MWIR. The launch locks were in place to prevent damage to struts during all of the flight qualification tests.

As part of the random vibration tests, low-level swept sine measurements were made to determine the test article structural dynamics. Swept sine measurements were made both prior to and following the high level runs to assist in verifying that the hardware did withstand the launch load environment without sustaining structural damage. Tests were run in three orthogonal directions, following military standards. These tests fulfilled the requirements mandated by the Jet Propulsion Laboratory (the experiment module integrator).

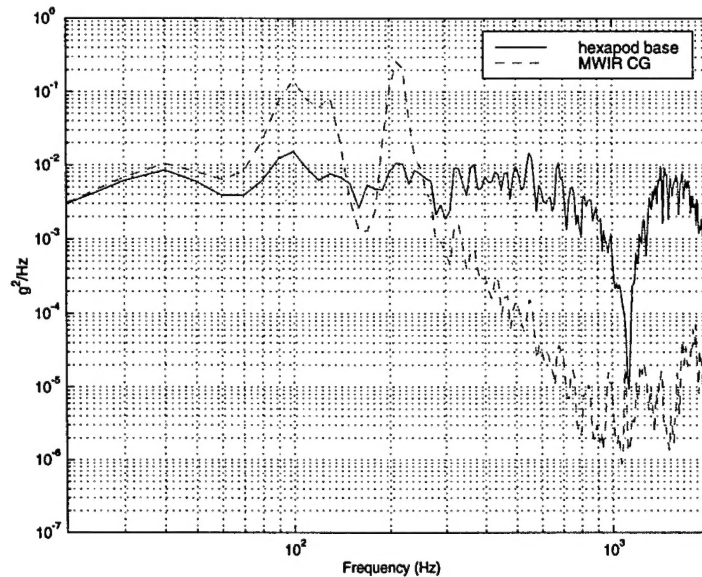


Figure 4: VISS thrust-direction random PSDs

Figure 3 shows two acceleration spectra measured when shaking in the Z (thrust) direction, one prior to, the other following the high-level random test. The close agreement is an indication that the high dynamic loads experienced during the random vibration test did not have an impact on the flight hardware integrity.

Two acceleration power spectral density (PSD) functions appear in Figure 4: one at the base of the VISS hexapod, the other at the test station close to the MWIR mass simulator center of mass. The base PSD is flat, except for a dramatic notch at 1.1 kHz due to an expander head mode. Hexapod resonances are evident in the 100 to 200 Hz range, as indicated by the peaks in the MWIR response in this frequency range. Isolation effects are seen above 250 Hz.

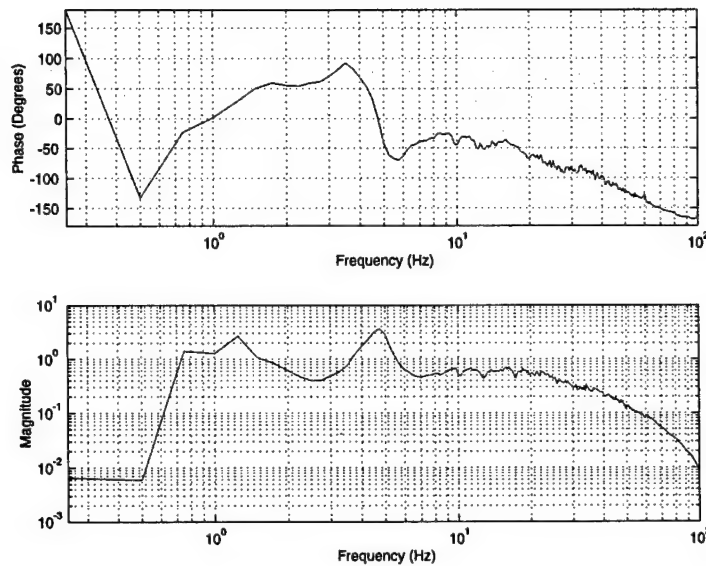


Figure 5: VISS acceleration transmissibility

## 2.2 Performance Tests

Extensive tests were performed on the VISS hardware during the performance experiment phase. Test setup structural dynamics was determined experimentally on a mockup of the VISS system prior to flight hardware delivery, and on the complete system including electronics and space qualified sensors. Two state-of-the-art gravity off-load systems simulated the free boundary conditions of space, as was required due to the very compliant VISS hybrid struts.

Acceleration transmissibility functions served as the system performance figure of merit in both closed and open-loop conditions. While conceptually this is a simple idea, it proved to be difficult to implement due to structural dynamics in the system, and the mechanical coupling in the hexapod.

Figure 5 shows a passive acceleration transmissibility measurement. The low frequency characteristic is dominated by the payload suspension modes on the struts. Strut stiffness was tuned to produce suspension modal frequencies around five Hz. The high frequency attenuation is apparent in this figure.

### 3. Satellite Ultraquiet Isolation Technology Experiment (SUITE)

The Satellite Ultraquiet Isolation Technology Experiment (SUITE) is a space flight technology demonstration scheduled to fly in spring or summer 1999. SUITE was developed under an Air Force sponsored Small Business Innovation Research (SBIR) project. The goal of SUITE is to demonstrate active-passive vibration isolation of a Stewart platform for space-based optical sensors using a stiff active system. SUITE consists of a the six-strut hexapod assembly (HXA) and data control system (DCS). Effort under this task focused on the transition of the hardware to final flight-ready status.

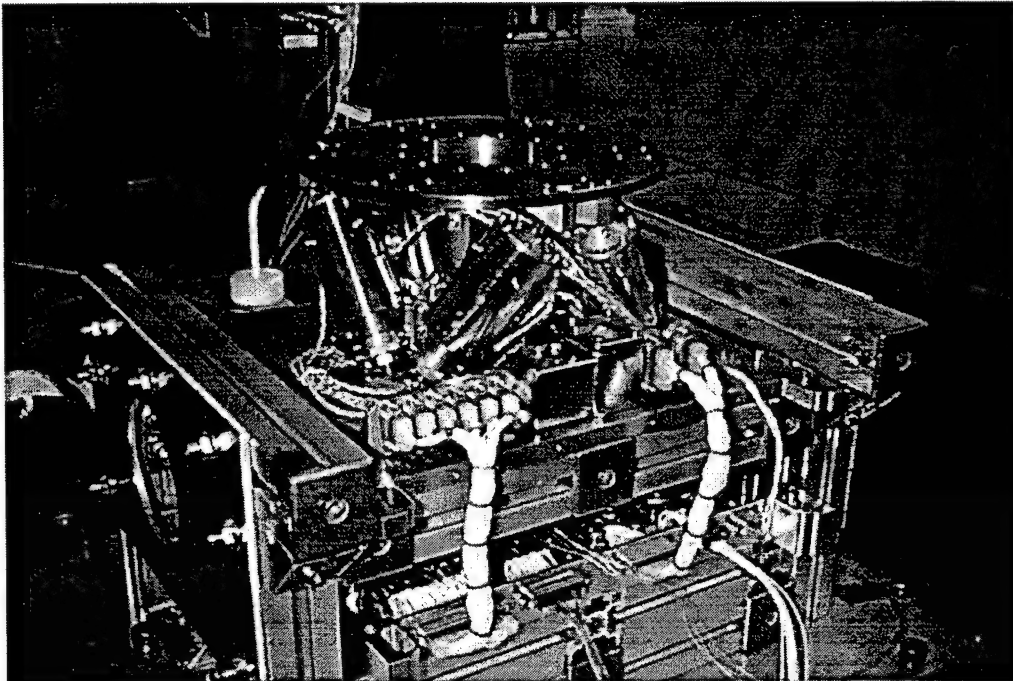


Figure 6: SUITE flight hardware

Technical goals included the following:

- Provide state-of-the-art closed loop control using low-cost sensors and electronics.
- Give the capability to up-load control laws when the system is on orbit.
- Eliminate a launch lock mechanism: the system must withstand the harsh launch vibration environment without additional restraints.
- Demonstrate 20 dB vibration isolation over a 100 Hz frequency range.

A total of twelve geophone sensors are included in the assembly: six (one in each strut) are used for closed-loop control, and triaxial "truth sensor" sets on both hexapod base and payload are used to quantify the system performance. Two on-board disturbance generators will be used to provide remotely commanded and controllable disturbances when on station.

CSA Engineering was responsible for design, fabrication and delivery of an operational system to the AFRL. Efforts were required in the following areas to support SUITE.

- Interaction with Surrey Satellite Technology Limited (SSTL).
- Hardware design and fabrication.
- System performance testing.
- Development of launch vibration specifications.
- Redesign of components for tolerance of high vibration levels.
- Modifications to cabling for flight.
- Development of user interface software.
- Assembly of a flight spare data control system.

SSTL is the British organization integrating the PICOSat satellite; SUITE is one of four payloads to fly on this satellite. CSA Engineering's interaction with SSTL included developing operational requirements, understanding the satellite communications bus, and plans for integrated spacecraft operation and tests. Reliable communication over the Controller Area Network (CAN) bus was finally established with a high speed parallel connection after previous operation with the lower speed serial connection. The launch vibration environment was also discussed with SSTL.

A software user interface was required in order to allow easy communication with SUITE, including visualization of data acquired during the testing. A rudimentary interface was already developed. Under this task, the interface was extended to show time domain vibration data as well as power spectral densities. In addition, a simple experiment list generator was written.

A spare data control system circuit board was fabricated. The DCS is the main electronic control system for SUITE that provides active vibration control as well as communication with the host spacecraft. The purpose of this flight-rated spare board was primarily to provide a backup in case of difficulties with the primary board. It also proved useful in ground testing and debugging because it allowed two boards to be tested in different ways at the same time. This board is now in use at the AFRL and will serve as part of the ground test system supporting the flight experiment.

This ASIAC task supporting the AFRL Space Vehicles Directorate proved to be instrumental in the development of another space flight experiment that will be instrumental in the demonstration of active vibration mitigation technologies. Objectives were met on this ambitious program.

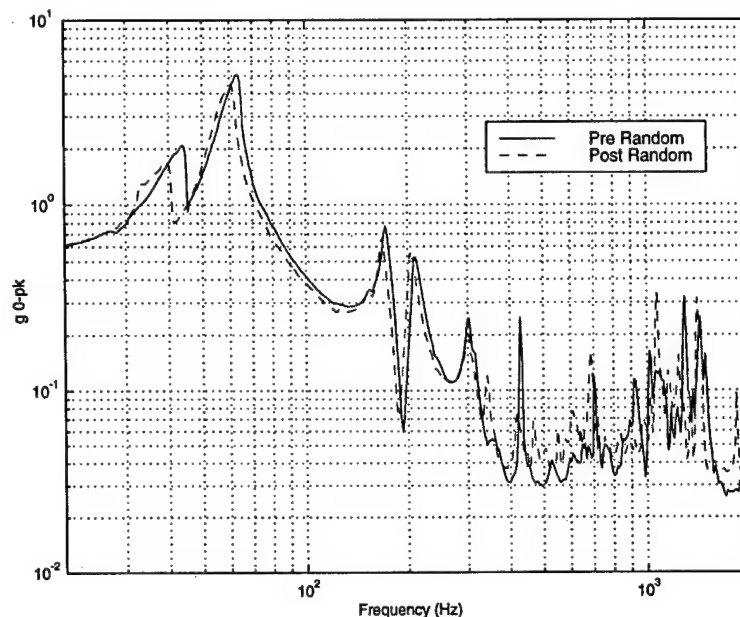


Figure 7: SUITE thrust-direction swept sine spectra

### 3.1 Flight Qualification Tests

Survival through launch vibration was an important design driver for SUITE. However, the launch vibration specifications were nonexistent until SUITE was almost fully constructed. Requirements were eventually defined in a series of discussions with SSTL, the Air Force Space Test Program, and the Aerospace Corp. representatives. A detailed random vibration and thermal/vacuum test plan was developed as part of this effort. The base disturbance spectrum defined in the test plan is identical to the one established for the VISS hardware, and was found to envelope expected vibration levels at the experiment base for any of a number of candidate launch vehicles.

An environmental test series was performed to verify the system robustness under a representative launch vibration environment and the taxing thermal conditions when on orbit. Figure 6 shows the SUITE system mounted on the shaker slip table for testing in a lateral direction. A structure seen in this figure is used to position the hexapod assembly and the electronics in the same fashion as they will be positioned on the spacecraft.

Figure 7 shows two payload Z-direction acceleration spectra from low-level (0.5 g 0-peak) sine sweep measurements, one prior to and the other following a high-level random input test. The slight differences between these two functions are due to the bumpering gaps increasing as a result of the high-level random shake. While there are differences between these two measurements, no drastic change in the structural dynamics is observed, indicating that the struts were unaffected by the random test.

Dynamics in the 40-45 Hz range is caused by rocking modes of the payload on the strut assembly. Strong response near 60 Hz is due to the plunge mode of the payload on the struts. The asymmetric character in both of these frequency ranges is a tell-tale sign of nonlinear behavior. SUITE payload response is subject to drastically different stiffness throughout its motion due to the bumpers. This payload response characteristic explains the behavior seen in Figure 7.

Initial vibration testing of the SUITE hexapod assembly resulted in component failures in the internal strut flexures making up the passive suspension system. The failures were attributed to excessive stresses resulting when the launch vibration bumpering system was itself damaged resulting in fatigue failure. Under this task, a new means of restraining the suspended payload was developed. It consisted of additional bumpering inside the struts and improved axial and radial bumpers surrounding the HXA payload.

The cabling used in SUITE to allow active vibration control was designed for flight, but during final testing there were two instances of short circuits. Therefore, the cabling was modified, including the removal of shield wires that were believed to be shorting. New harnesses were assembled and installed on the flight system.

## 4. UltraLITE

The Ultra Lightweight Imaging Technology Experiments (UltraLITE) was supported as part of this Task. UltraLITE experimental objectives include developing technologies to deploy structures for segmented mirrors, and to control mirror position within nanometer accuracy. Interaction of the boom dynamics with the control system has posed significant technical hurdles to the UltraLITE team, based at Kirtland Air Force Base, New Mexico. UltraLITE support using this ASIAC Task proved to be advantageous in the aggressive program schedule.

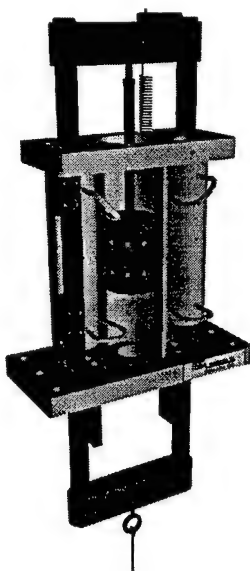


Figure 8: Suspension system used for UltraLITE

The UltraLITE boom is cantilevered off a backup structure, itself mounted to a large seismic mass. A pneumatic support system reduces seismic mass response to laboratory floor vibration. Piezoelectric actuators and sensors are used in the UltraLITE control system for mirror positioning.

Precision space-qualified hinges, fastened at one end of the boom, have a 100-pound load limit: well below the 400-pound boom and mirror weight. CSA Engineering implemented a gravity off-load system that protects the hinges, while simulating the free boundary conditions like that of space. In addition to protecting the hinges from loads above their design limits, the off-load system provides a method to produce large-angle deployment and imparts repeatable reaction loads at the boom center of mass. The off-load system approach involves a two-stage design: an electric winch is used for the large-angle boom deployment, and the boom is "handed over" to a sophisticated off-load device as it approaches the horizontal (or home) orientation. Very compliant flexures limit reaction forces to the boom and allow the fixturing to clear the mirror mass simulator when the boom is in the undeployed configuration.

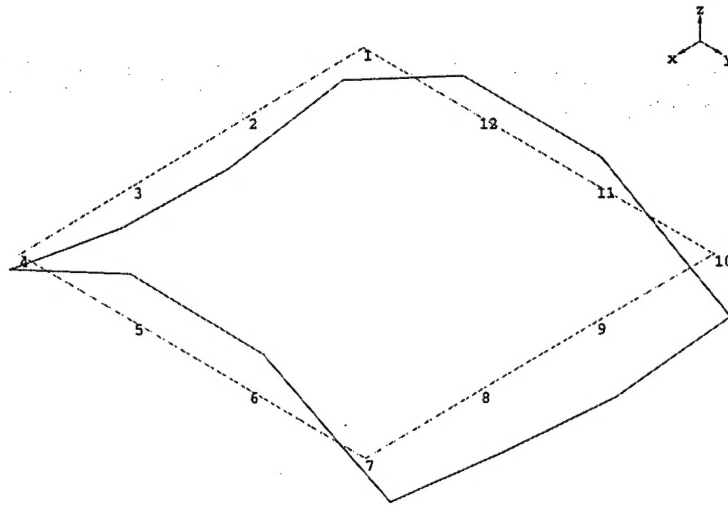


Figure 9: Bending mode shape of seismic mass used for UltraLITE

Figure 8 shows a rendering of the suspension system used to off-load the UltraLITE boom. The system exploits high performance air journal bearings to achieve the required centering stiffnesses with unmeasurable friction. A large reservoir volume connected to the suspension device provides the extremely soft pneumatic spring rate that simulates the lack of restraining forces in space. Lightweight Kevlar twine connects the suspension system to the boom-hang-point fixture thereby eliminating imposing moments on the test article.

Modal tests performed under this task assisted the UltraLITE team in interpreting system-level results and provided direction to laboratory facility modifications. This approach increased experimental capabilities to achieve the challenging requirements in the UltraLITE program. Figure 9 shows a measured mode shape from a test of the 37-ton seismic mass used in the UltraLITE experiment. Knowledge of the seismic mass dynamics was key to interpreting measurements on the boom.

## 5. Starfire Optical Range

The Starfire Optical Range (SOR), located on Kirtland Air Force Base, New Mexico, includes two state-of-the-art telescopes used for astronomical and Department of Defense research. The SOR telescopes have very high slewing rate capacities, required to track satellites with low-elevation-angle trajectories.

Adaptive optic technology developed on the SOR 1.5-meter telescope has revolutionized the imaging quality achievable with ground-based telescopes. High-gain adaptive optics (AO) loops using a so-called guide star correct for scintillation caused by atmospheric turbulence. Performance with these AO loops closely rival those acquired with the Hubble Space Telescope, where atmospheric aberrations do not

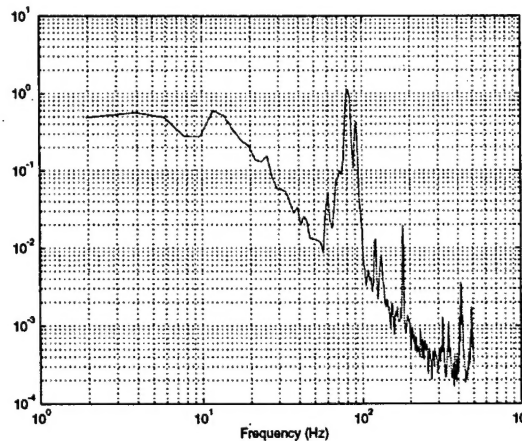


Figure 10: SOR measured centroid PSD with adaptive optics loops closed

degrade imaging.

The 1.5-meter telescope has shown "intermittent" jitter that limits image resolution when the AO loops are closed. Possible causes of mechanical vibration in the 60-to-100 Hz range were investigated as part of another Air Force contract; the ASIAC efforts were directed at integrating a passive damping-based structural modification, documenting its performance, and performing additional diagnostic testing. Support of the AFRL on this challenging program has demonstrated that a noise source is the cause; the structure is not at fault. Future efforts are planned to assist SOR personnel to pinpoint the cause and realize a solution.

Figure 10 shows a measured optical centroid power spectral density function (PSD) with the AO loops closed. From this measurement, it is clear that jitter in the troublesome frequency range is a significant limitation to the scientific capability of the facility.

Figure 11 shows the finite element model developed as part of the damping treatment design efforts. The model includes the optical tube surrounding the primary, secondary and tertiary mirrors in the Cassigrain-type telescope. Metering rods running parallel to the optical axis register the secondary mirror precisely to the primary mirror. A four-bladed "spider" supports the secondary mirror. The spider has high stiffness in directions contributing to secondary mirror tilt while having a very low projected area that forms a shadow on the image.

Modal analysis on the 1.5-meter telescope has shown that metering rod bending modes occur in the frequency range of concern. Due to the influence of these modes on secondary mirror tilt, a passive damping-based structural modification was designed and implemented to decrease the resonant response associated with these metering rod modes. Figure 12 shows a mode shape estimated from measurements.

The structural modification was integrated and its performance verified as part of this effort.

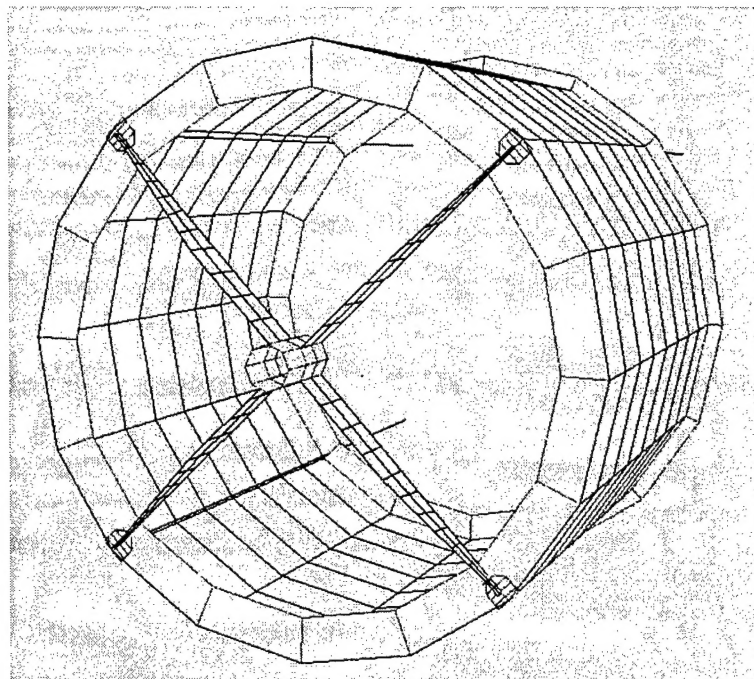


Figure 11: SOR finite element model

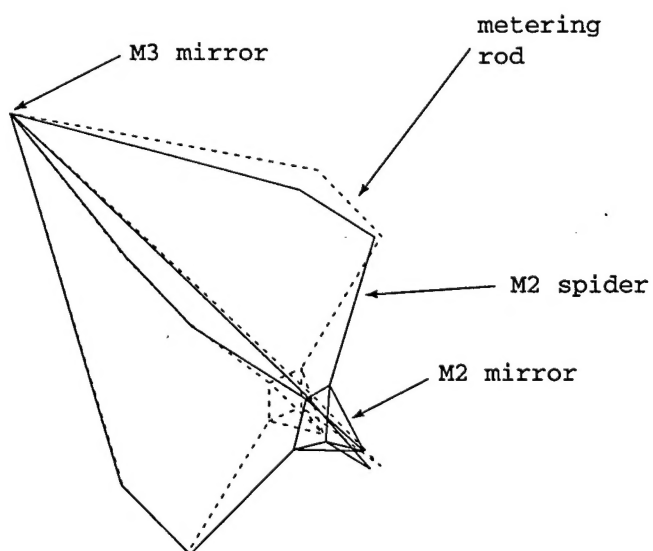


Figure 12: Measured mode shape of SOR secondary metering structure

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